Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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Discussion

The law of regression to the tail: How to survive Covid-19, the climate crisis, and other disasters

Bent Flyvbjerg

Major Programme Management, University of Oxford, UK

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ABSTRACT

Regression to the mean is nice and reliable. Regression to the tail is reliably scary. We live in the age of regression to the tail. It is only a matter of time until a pandemic worse than covid-19 will hit us, and climate more extreme than any we have seen. What are the basic principles that generate such extreme risk, and for navigating it, for government, business, and the public?

1. The law of regression to the tail

Sir Francis Galton coined the term "regression to the mean" – or "regression towards mediocrity," as he originally called it, sometimes also called "reversion to the mean." It is now a widely used concept in statistics, describing how measurements of a sample mean will tend towards the population mean when done in sufficient numbers, although there may be large variations in individual measurements.

Galton illustrated his principle by the example that parents who are tall tend to have children who grow up to be shorter than their parents, closer to the mean of the population, and vice versa for short parents.[1]

In another example, made famous by Nobel-Prize winner in economics Daniel Kahneman, pilots who performed well on recent flights tended to perform less well on later flights, closer to the mean of performance over many flights. This was not because the pilots' skills had deteriorated, but because their recent good performance was due not to an improvement of skills but to lucky combinations of random events.

There is nothing as practical as a theory that is correct. Regression to the mean has been proven mathematically for many types of statistics and is highly useful in health, insurance, schools, on factory floors, in casinos, and in risk management, e.g., for flight safety.

But regression to the mean presupposes that a population mean exists. For some random events of great social consequence this is not the case.

Size-distributions of pandemics, floods, wildfires, earthquakes, wars, and terrorist attacks, e.g., have no population mean, or the mean is ill defined due to infinite variance. In other words, mean and/or variance do not exist. Regression to the mean is a meaningless concept for such distributions, whereas what one might call "regression to the tail" is meaningful and consequential.

Regression to the tail applies to any distribution with non-vanishing probability density towards infinity. The frequency of new extremes and how much they exceed previous records is decisive for how fat-tailed a distribution will be, e.g., whether it will have infinite (non-existent) variance and mean.[2] Above a certain frequency and size of extremes, the mean increases with more events measured, with the mean eventually approaching infinity instead of converging. In this case, regression to the mean means regression to infinity, i.e., a non-existent mean. Deep

[1] Although Galton's theory proved right, the example he used to illustrate it proved flawed, because the height of a child is not statistically independent of the height of its parents, due to genetics unknown to Galton. Nevertheless, it is clear what Galton was trying to prove and it turns out he was right, including for statistically correct examples.

[2] "Fat tailed" is not a well-defined, or even consistently used, concept in statistics and mathematics, not to speak of social science and psychology. A common definition specifies fat tails as the tails of a probability distribution with a large skewness or kurtosis, relative to that of a normal (Gaussian) distribution. The larger the skewness or kurtosis, the more fat-tailed the distribution is said to be, with the most fat-tailed distributions, e.g., Pareto distributions, having not only infinite skewness and kurtosis but also infinite – i.e., non-existent – variance and mean. The terms "heavy tailed" and "long tailed" are sometimes used synonymously with "fat tailed." For the science of fat tails, see Mandelbrot (1997); Mandelbrot and Hudson (2008); Taleb (2019, 2020), Clauset et al. (2009), and West (2017).

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disasters – e.g., pandemics, floods, droughts, wildfires, earthquakes, landslides, avalanches, tsunamis, and wars – tend to follow this type of distribution. So do crime, terrorist attacks, blackouts, financial markets, debt, bankruptcies, and cybercrime, together with less disastrous but financially highly risky ventures like hosting the Olympics, building nuclear power plants, high-speed rail systems, hydroelectric dams, new cities, and even something as apparently innocuous as procuring new IT systems, the latter being a serious bug in current worldwide digitization efforts.

I suggest we name this phenomenon – that events return to the tail in sufficient size and frequency for the mean to not converge – "the law of regression to the tail." The law depicts a situation with many extreme events, and no matter how extreme the most extreme event is, there will always be an event even more extreme than this. It is only a matter of time until it appears.

I further suggest that regression to the tail is the new normal. We live in the age of regression to the tail. Tail risks are becoming increasingly important and common because of a more interconnected and fragile global system of human interaction for travel, commerce, finance, etc., but also because the walls are coming down between natural and human systems, with humans impacting nature at a global scale for the first time in history, not least in terms of climate change. The pandemic and the climate crisis are presently the two most significant manifestations of the law and age of regression to the tail.

2. Covid-19 as regression to the tail

Prudent decision makers will not count on luck – or on conventional Gaussian risk management, which is worse than counting on luck, because it gives a false sense of security – when faced with risks that follow the law of regression to the tail. Instead, decision makers will want to do two things: (a) "cut the tail," to reduce risk by mitigation, and (b) practice the precautionary principle, i.e., avoid tail risk altogether by taking a cautious approach.

In any given situation, prudent decision makers and their risk managers must be able to decide whether they face a situation with regression to the mean (mild Gaussian risk) or regression to the tail (extreme fat-tailed risk), and – most importantly – to never mistake the latter for the former. This is a difficult task, because a host of cognitive and other biases – including simple wishful thinking and power structures that do not welcome truth – trick us into seeing mild risk when risk is in effect wild.

To illustrate, consider the current covid-19 pandemic. Cirillo and Taleb, 2020 argue that pandemics (measured by number of deaths) seem to follow a Generalized Pareto Distribution, i.e., a classic fat-tailed distribution. The law of regression to the tail is consequently pertinent, with three important implications.

First, the covid-19 pandemic was entirely predictable. Indeed, the pandemic was predicted years ago by people as different as Nassim Nicholas Taleb, author of *Incerto*, philanthropist Bill Gates, and numerous epidemiologists who have, deservedly, had a field day as what-did-I-say prophets, after being ignored for years by government, business, and media.

Second, if you understand regression to the tail it is clear what the main mitigating measures should be once a pandemic develops, namely: (a) cut the tail (by breaking the chain of transmissions through, e.g., lockdowns, personal protection equipment like face masks, testing, development of vaccines, etc.) and (b) the precautionary principle (rather a lockdown too many than one too few) – rolled out *immediately*, at *speed*, and at *scale*, worldwide.[3]

Why does regression to the tail suggest precisely these measures before others? Because the measures derive directly from tail characteristics, including the fact that the spread of pandemics follow an exponential growth curve. The tail therefore needs to be mitigated immediately and directly, and the mentioned measures do this most effectively. If the measures are ignored, the consequences are dire, because 10,000 covid-19 infections today will be 80,000 infections just nine days later, and 640,000 infections another nine days after that, etc., following exponential growth.

To illustrate, consider the UK's slow response to the pandemic. Giving evidence before the UK House of Commons Science and Technology Select Committeein June 2020, the prime minister's former top scientific adviser on the coronavirus outbreak and leader of Imperial College's Covid-19 Response Team, professor Neil Ferguson, testified, "had we introduced lockdown measures a week earlier, we would have then reduced the final death toll by at least a half," which translates into a minimum of 32,100 UK lives lost unnecessarily due to sluggish government (Hughes, 2020). For perspective, even if the UK had introduced lockdown measures a week earlier they would still have been slower than most other European nations, including neighboring Denmark and Norway. At the time of writing, excess deaths[4] from the virus in the UK was 65,700, compared with 200 in Denmark and zero in Norway, and higher than for any other European country with data (Ritchie et al., 2020).[5]

Britain's favorite crisis heuristic – "keep calm and carry on" – proved entirely imprudent in the face of regression to the tail. "Act *now*, at *speed*, and at *scale*," is the prudent response. This holds true not only for pandemics, but for the climate crisis and other systemic tail risks.

However, lockdowns, masks, testing, etc. happen to be contested measures. In the United States, wearing a face mask was politicized and became yet another issue polarizing an already heavily polarized nation. Not until July 2020 would US President Donald Trump wear a face mask in public, just as he openly questioned the value of testing and lockdowns.

In the United Kingdom, Prime Minister Boris Johnson explained on national TV that lockdowns and telling people what to do would not sit well with the British liberal tradition. Brits should be trusted to use common sense, which for the prime minister himself meant – also documented on TV – continuing to shake hands well into the second week of March 2020 (Mason, 2020; McGuinness, 2020). At a Downing Street press conference the prime minister explained his approach, in what can most benevolently be described – not only in hindsight, but at the time – as a tragically misguided attempt to instill trust with the public: "I can tell you that I'm shaking hands continuously … I was at a hospital the other night where I think there were actually a few coronavirus patients and I shook hands with everybody, you'll be pleased to know, and I continue to shake hands" (Express and Star, 2020). Unsurprisingly, the prime minister was soon infected, and in turn likely infected others, before ending up in intensive care for an entirely avoidable near-death experience (BBC, 2020).

For Johnson, as for anyone, the virus clearly did not care whether he

[3] In addition, the closing of wet markets and changes to the food processing industry would help prevent epidemics and pandemics from developing in the first place.

[4] Excess deaths, a.k.a. excess mortality, is considered the most reliable measure of deaths from covid-19 and the best measure for cross-national comparison. It is calculated for a country or a city as deaths during the pandemic minus the average number of deaths over the previous five years for the same period. It measures, in short, how many more people died during the pandemic, compared with before. It is not a perfect measure, but the best there is for now.

[5] During the pandemic in the UK, it was common to see people, including highly educated commentators, trying to explain the steep number of UK deaths by a high level of obesity and general low level of health in the UK population compared with other nations. Such explanations are misguided. It is not that obesity and general health do not matter. But they are of marginal importance in the early stages of a pandemic when speed and exponential growth of infections is all-important, as rightly pointed out by Professor Neil Ferguson above.

contested the measures to mitigate it or not, or whether he acted foolishly or not. Such is the nature of fat-tailed risk. It is what it is. You will find it difficult to postulate another reality in the face of it. It will not be ignored or swept under the carpet. Nor will it be mastered by post-truth bluster or a stiff upper lip. Leaders who depend on such artifices to govern will appear incompetent when faced with fat-tailed risk, as happened for Johnson and Trump. Contested or not, the most effective measures for mitigating pandemic fat-tailed risks are cutting the tail and general precaution, enacted immediately, at speed, and at scale.

Initially, the measures need to be implemented across the board. This unfortunately has grave consequences for the economy. But to not implement the measures, or to do so inefficiently, has even graver consequences. To illustrate, at the time of writing just over 180,000 people had died from covid-19 in the United States. The US government sets the economic value of a saved life at 10 million dollars for policy prioritization. That's 1.8 trillion dollars destroyed by covid-19, growing at 5–15 billion dollars a day at the time of writing. That is massive wealth destruction and the numbers show that from even a narrow cost-benefit point of view it makes good sense to mitigate as described. As long as it costs less than one billion dollars to save 100 lives, mitigation should continue, from a cost-benefit perspective, and you can save a lot of lives for one billion dollars in a pandemic, if the money is spent on the right measures. Billions, or even millions, spent up front will save trillions later, as a general heuristic, which derives directly from the exponential nature of virus growth.

Nevertheless, lockdowns must be eased as quickly as possible to limit damage to economic and social life, without letting the virus loose again. As soon as data are available that allow the calculation of viral reproduction numbers[6] for specific geographies and communities, measures can be targeted more precisely, limiting unnecessary damage to the economy and social affairs. For example, once initial lockdowns have brought the virus under control, further lockdowns will be necessary only in an ad hoc manner for geographies, communities, and time periods for which infections have spiked up again. In theory, it might be possible for whole nations to bring the virus under control solely by the use of face masks, possibly combined with social distancing, with everyone using masks at first, until the viral reproduction number has been brought below 1, after which the use of masks can ease up, to be reintroduced only for geographies, communities, and time periods for which the viral reproduction number climbs back above 1, until the number has been driven below 1 again, etc. For such measures, the difference between success and failure will be small, viz., the difference between being just below or just above a viral reproduction number of 1, which stresses the importance of getting the measures right. Following this type of approach, negative economic and social consequences from the pandemic can be significantly reduced.

Third, contingencies must be in place to allow speedy scale-up. When leaders finally understood that covid-19 was a fat-tailed phenomenon and began to make the proper decisions, it turned out that health services, government, and businesses were dismally underprepared, to a degree that things as basic as supplies of face masks, gowns, and other protective gear for health workers immediately ran out. Similarly, testing and tracking capacity was not in place, but had to be developed in fits and starts. The lack of reserves made it impossible to scale up mitigation quickly and effectively, resulting in a failure to curb the virus – just like a bank without reserves would fail in a crisis.

Innovative thinking is needed for both mitigation measures and contingencies, especially before the fat tail strikes. Once it does, things will often be too hectic to allow for effective innovation. E.g., when a virus is spreading exponentially through a population, it is too late to think about better and more protective gear, tracking, testing, etc., although some thinking and innovation "on your feet" may be possible and valuable. But it would be like building the proverbial airplane while flying it, which is not a good idea, but which was nevertheless the situation for covid-19. Ex ante innovative thinking and preparedness were almost entirely absent, which is a main reason for the dismal outcome of the pandemic in many countries, including the United States and the United Kingdom.

After the pandemic, full-on innovation will be very much needed again, regarding the steps humanity must make to lead economies and societies to recovery and a better future, including better management of tail risk. More about this below.

3. A top 10 of regression to the tail

Table 1 shows a Top Ten list of phenomena that are subject to the law of regression to the tail, ranked by the fatness of tails. All phenomena in the table have infinite variance, i.e., they are highly fat tailed.

We see that the fattest tail – indicating the largest and most frequent regressions to the tail – are found for earthquakes (measured by intensity), which for good reasons are often considered the archetypical case of a power-law distributed deep disaster. Pandemics (measured by number of deaths) are somewhere in the middle, and electricity blackouts (measured by number of customers affected) at the bottom, but still very fat-tailed and impactful.

We note that floods and forest fires are both subject to regression to the tail. The same holds for droughts, hurricanes, landslides, ice melt, sea-level changes, and other phenomena closely related to the climate crisis, not included on the list. This tells us that understanding regression to the tail and how to mitigate its specific manifestations for climate will be key to mitigating the climate crisis. Here it is worth remembering that regression to the tail for the climate crisis will be just as indifferent to human ignorance and folly as we saw regression to the tail was for covid-19 above. We either cut the tail and practice the precautionary principle for the climate crisis, or we die in large numbers and destroy our economic and social fabric, again.

4. Policy implications

Rebuilding the economy after the covid-19 pandemic will be subject to the law of regression to the tail, if less dramatically so than the pandemic itself. Loss of life will hopefully soon fade as a main risk. But financial fragility, wealth destruction, and problems with debt will

Table 1
Top 10 phenomena that are subject to the law of regression to the tail, ranked after fatness of tails. The higher on the list, the fatter the tail, and the larger and more frequent regressions to the tail will be. All phenomena have infinite variance. The table shows phenomena for which data were available.

Phenomenon	Described in
1. Earthquakes (intensity as Richter Scale maximum peak)	Clauset et al. (2009)
2. Cybercrime (financial loss)	Maillart and Sornette (2010)
3. Wars (number of battle deaths per capita of involved nations)	Newman (2005)
4. Pandemics (number of deaths)	Cirillo and Taleb (2020)
5. IT procurement (percentage size of cost overrun)	Flyvbjerg et al. (2020a)
6. Floods (volume of water)	Malamud and Turcotte (2006)
7. Bankruptcies (percent of firms per year per industry)	Hong et al. (2007)
8. Forest fires (size of area affected)	Clauset et al. (2009)
9. Olympic Games (percentage size of cost overrun)	Flyvbjerg et al. (2020b)
10. Blackouts (number of customers affected)	Clauset et al. (2009)

[6] The viral reproduction number, R_0, is the number of infected people that are expected to occur on average as a result of infection by a single individual. So if one person develops the infection and passes it on to two others, the R_0 is 2. If the average R_0 in a population is greater than 1, the infection will spread exponentially. If R_0 is less than 1, the infection will spread only slowly, and will eventually die out. The higher the value of R_0 above 1, the faster an epidemic will spread through a population.

continue to be key risks for a while.

The massive stimulus spending programmes that governments use to restart economies in recession typically comprise giant construction and investment projects with fat-tailed financial risks, like multi-billion-dollar megaprojects in IT, transport, energy, water, education, housing, health, and defense (Flyvbjerg, 2017).

Some projects are more fat-tailed than others, i.e., they are more susceptible to the law of regression to the tail. Data analytics should be used to separate fat-tailed projects from thin-tailed ones, and stick with the latter whenever possible. We know how to do this.

For instance, nuclear power plants are bespoke, slow to build, and fat tailed for financial and safety risks; whereas wind farms and energy storage are modular, fast, and thin tailed. By choosing wind over nuclear, the risk of regression to the tail will be significantly reduced, and climate goals will be achieved sooner.

Every investment alternative must be assessed in this manner to ensure that stimulus spending becomes a boost instead of a drag on the economy. The latter is happening more often than we like to think (Ansar et al., 2014, 2016, 2017; Detter and Fölster, 2015; Flyvbjerg, 2017; Kanter, 2015; Ren, 2017).

In addition to this, leaders should think about investment priorities coming out of the crisis and how to best restart the economy, taking into account what we have learnt from the crisis. Such priorities include:

4.1. Re-building health and social care services

The crisis has brought many health and care facilities, including for the elderly, to a breaking point, revealing that the safety of both employees and patients was compromised in ways that most would not have imagined. There will be a requirement to invest in people and facilities to rebuild these services.

4.2. Decarbonizing the economy

The crisis must be used to accelerate the transition to an electric, zero-carbon economy. This includes (a) investments in renewable energy (and maybe nuclear, if it can be made fast and safe) for powering industry and households; (b) electrification of trains, trucks, public transport, and cars; and (c) investments to improve true sustainability of farming, food manufacture, housing, and commercial real estate.

4.3. Digitization

We are unlikely to return to the same state of the world as when we entered the pandemic. Remote working has the potential to become more prevalent after the crisis. Investments might shift from face-to-face working (and lower the cost of office real estate and time for commuting). Stimulus spending should focus investments on the enablers of this new approach to work, e.g., 5 G rollouts, broadband infrastructure, satellites for global reach, server farms for adequate capacity, etc.

4.4. Traffic reduction measures

Few investments have historically been made to change the demand for transportation infrastructure. Investments have tended to expand supply-side capacity following the heuristic "predict and provide". Lockdowns and stay-at-home measures have reduced traffic and pollution levels. The gradual restart of the economy should be used to prevent traffic demand from returning to pre-crisis levels, turning the focus upside down from supply-side to demand-side management, following the heuristic "predict and prevent."

4.5. Mega compensation schemes

There is likely to be a host of post-pandemic litigation, including massive class-action suits, to recoup losses or seek redress for negligence. To prevent this from running amok and hampering the restart of the economy, comprehensive compensation and settlement schemes should be designed and ready for implementation.

The above measures and priorities do not lessen the urgency for prudence, here understood as Aristotelian *phronesis* (Flyvbjerg, 2001; Flyvbjerg et al., 2012). In fact, it raises its importance, especially as - arguably and sadly – *phronesis* does not characterize senior and middle management decision making more generally and at times of crisis. This is the case for even top political leaders like presidents and prime ministers, as we saw above, despite the fact that they need *phronesis* more than anyone, or their citizens will suffer for the lack of it, as they do at present. Rescher (1995: 177) rightly observes that randomness is best influenced by prudence. With the extreme randomness generated by regression to the tail, prudence therefore becomes particularly important, in the shape of common caution, hedging one's bets, keeping contingencies, providing insurance for all, and similar prudent measures.

Finally, to be effective, prudence must be based on dialogue and deliberation, something stressed already by Aristotle. The social and economic infrastructure must be in place to facilitate the development of new, future approaches to pandemics and the climate crisis, shaping a new world in the process. If nothing else, efforts to prepare for and avoid the next pandemic would need a very strong, persistent, and ongoing rhetoric to be funded over time to keep attention on fat-tail phenomena alive and institutionalize it across policy, business, and everyday life, in the absence of events which justify such expenditure. This is another front on which we have failed miserably in the past and on which we cannot afford to fail in the future, as the world gets evermore connected.

5. Implications for the climate crisis

We are lucky that the covid-19 pandemic is not worse than it is – specifically that mortality for those infected is not higher – because everything we know about pandemics tells us mortality might as well have been significantly higher, and that sooner or later there will be a pandemic like that, worse than the worst to date. That's the nature of fat-tailed risk as depicted by the law of regression to the tail.

A positive way to view covid-19 is to see it as a much-needed opportunity for humanity to exercise its skills in managing regression to the tail. We need those skills to survive as a species and to build a world that is worth surviving in. Covid-19 may be seen as a dress rehearsal for how to deal with the climate crisis; a crash course in how to mitigate regression to the tail. When we study the pandemic carefully it offers us the basic principles needed to mitigate other fat-tailed risks, the climate crisis included. Seen from this perspective, despite its indisputable tragedy, covid-19 is a much-needed, large-scale survival exercise for humankind on planet earth.

Mitigating the climate crisis involves "thinking in long time scales while acting with furious urgency," as observed by Mingle (2020: 51). Science tells us we have maybe a decade or two where we can still influence global warming, ice melt, and sea level change. Then it will be too late. Missing this window of opportunity is a scary prospect. The good news is, however, that covid-19 has served as a wake-up call and has demonstrated that the world, or at least parts of it, are capable of the speedy, concerted effort and massive involvement from government, science, business, and banks that are necessary to solve an urgent problem that threatens humanity as such. We did not know this pre-covid-19, because the ability had never been tested.

The covid-19 pandemic has taught us what to do and not to do in the face of regression to the tail. Two lessons stand out.

First, everyone needs to be honest about, and keep in mind, that there will be more extreme events in the future. There will be more pandemics, and one of these will be worse than covid-19. This uncomfortable fact follows directly from the fat-tailed distribution of pandemics and the associated law of regression to the tail.

Second, once leaders and citizens understand that pandemics involve regression to the tail, they will also understand how to handle the next pandemic. Specifically, four effective mitigation measures apply, when faced with regression to the tail:

a) cutting the tail, by eliminating specific tail risks;
b) using the precautionary principle, i.e., avoiding tail risk by taking a cautious approach;
c) making sure the necessary contingencies are in place; and
d) acting immediately, at blitz-like speed, and at scale, when the tail rears.

The two lessons and four measures are general. They derive directly from the mathematical and statistical properties of fat-tailed distributions and apply not only to pandemics, but to all phenomena that are subject to the law of regression to the tail, for instance: floods, droughts, wildfires, earthquakes, landslides, tsunamis, wars, avalanches, crime, terrorist attacks, blackouts, big infrastructure projects, and more.

In sum, covid-19 is a stark reminder of three things.

First, extreme events will haunt humankind, over and over. It is only a matter of time until an event will occur that is more extreme than the most extreme to date. This is the "law of regression to the tail."

Second, historically we have been dismal at managing regression to the tail, today maybe more than ever with the lean, optimized, and highly interconnected global system we have created.

Third, with the tail risks currently facing humanity in terms of, e.g., climate, the pandemic, rebuilding the economy after the pandemic, and global debt, we cannot afford leadership that ignores or underestimates regression to the tail.

Using covid-19 to truly understand the basic principles of regression to the tail, and then putting those principles effectively to work in mitigating the major risks we currently face – paramountly the climate crisis – may well be key to our survival as a species, or at least survival of life as we know it. If we do this, covid-19 would not be a wasted crisis.

Declaration of Competing Interest

The author reports no declarations of interest.

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